UNITED STATES PATENT APPLICATION

FOR

POLARIZATION MODE DISPERSION COMPENSATING APPARATUS, SYSTEM, AND METHOD

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Polarization Mode Dispersion Compensating Apparatus, System, and Method

BACKGROUND OF THE INVENTION

Field of Invention

The present invention relates to optical communications systems. More particularly, the present invention relates to polarization mode dispersion compensating systems and methods.

Description of Related Art

Polarization mode dispersion (PMD) is a well-known problem caused by the undesired, residual birefringent properties of optical fibers. Despite the attempts of optical fiber manufacturers to eliminate PMD, a residual amount of PMD is still present. Moreover, there are a variety of existing fiber plants having fibers not optimized to reduce PMD.

Essentially, PMD causes the two principal states of polarization to propagate along an optical fiber at different rates. The polarization of an optical signal may be expressed in terms of two components (the so-called "principal states of polarization" (POS)). The two principal polarization states each experience different propagation delays as they propagate down a length of optical fiber due to the residual birefringence of the fiber. The result of the time delay (τ) between the two principal states (also referred to as differential group delay, or DGD) is that the signal is distorted. The time delay (τ) may be on the order of 10-20ps for a 100km fiber

More accurately, DGD exhibits a gaussian distribution. DGD values, such as the 10-20ps mentioned above, are usually a mean value of this gaussian distribution. However, the Gaussian distribution means that there is a likelihood of a DGD value much larger than the mean. Such large DGD values can cause optical signal pulses (composed of both principal polarization states) to broaden to such an extent that intersymbol interference occurs and the bit error rate (BER) rises.

In addition, higher data rates and longer transmission distances make even small PMD values a more significant problem than in the past. For example, at 10Gb/s only 100ps separates each pulse. Thus, a 50ps PMD could easily cause a bit error. The progression to 40Gb/s and higher will make PMD compensation an important problem to solve.

Exacerbating these problems is the fact that PMD varies with time, fiber temperature, and fiber stress. For example, a technician moving a fiber will stress the fiber and induce fluctuating PMD. Temperature cycling will also cause a fluctuating PMD. Thus, a PMD compensator having a fixed amount of counter-PMD will not adequately offset the time-varying PMD.

To address these problems, various PMD compensation schemes have been invented. Many of these schemes employ variable time-delay elements that subject one of the two principal polarization states to a variable delay in order to align the phases of the principal states.

Fee et al. (USP 5,859,939) is an example of such a variable delay element approach. Fee's polarization beam splitter splits the input beam in order to detect the delay between the principal polarization states. Incremental delay elements made from different lengths of optical fiber are then switched into the optical path of one (or both) of the principal polarization states in order to align the phases thereof. The phase-compensated principal states are then combined, hopefully with a reduced PMD.

Hakki (USP 5,659,412) is another example of such a variable time-delay element approach. Hakki uses a polarization beam splitter to split the incoming signal into transverse electric (TE) and transverse magnetic (TM) polarized components after a polarization controller aligns the PSPs of the received optical signal with the polarization axes of the beam splitter. The TM component is delayed by a variable electrical delay element. A phase detection circuit measures a phase difference between the components and is used to control the variable electrical delay element and the polarization controller. The compensated components are then combined and fed to a receiver (decision circuit).

SUMMARY OF THE INVENTION

The invention corrects the polarization mode dispersion of an input signal by controlling a polarization mode dispersion compensator having a variable PMD so as to generate a PMD vector of equal magnitude but opposite direction to the PMD vector of the input signal. Mathematically, the input signal has a PMD that may be expressed as a vector on the Poincare sphere having an associated magnitude and direction (θ,ϕ). Generally speaking the invention controls a polarization mode dispersion compensator to generate a counter-PMD vector of equal magnitude and opposing direction $(-\theta,-\phi)$ thereto.

More specifically, the invention may be implemented as a polarization mode dispersion compensating apparatus, including: a polarization mode dispersion compensator optically coupled to an input port and receiving an input optical signal having polarization mode dispersion and a wavelength dither, the polarization mode dispersion compensator having a variable polarization mode dispersion; a polarimeter optically coupled to the output of the polarization mode dispersion compensator and outputting an electrical signal representing polarization states of the optical signal; and a controller operatively coupled to the polarimeter and the polarization mode compensator, the controller receiving the electrical signal from the and controlling the polarization mode dispersion compensator according to the electrical signal to compensate for the polarization mode dispersion of the input optical signal.

Furthermore, a signal source for generating the input optical signal with the wavelength dither may be used wherein the input optical signal is transmitted across optical fiber and/or components that cause the input signal to have the polarization mode dispersion.

The polarimeter may include a first polarizer optically coupled to the polarization mode dispersion compensator, the first polarizer plane polarizing an optical signal output from the polarization mode dispersion compensator at first polarization angle; a second polarizer optically coupled to the polarization mode dispersion compensator, the second polarizer plane polarizing an optical signal output from the polarization mode dispersion compensator at a second angle different than the first angle; a third polarizer optically coupled to the polarization mode dispersion compensator, the third polarizer circularly

polarizing an optical signal output from the polarization mode dispersion compensator; and three photodetectors receiving the outputs of the first, second and third polarizers

In addition, the controller may control the polarization mode dispersion compensator so as to minimize a sum of the squares of the first, second and third detection signals to compensate for the polarization mode dispersion of the input optical signal.

Moreover, the controller may utilize an adaptive learning algorithm to minimize the sum of the squares of the first, second and third detection signals to better compensate for the polarization mode dispersion of the input optical signal.

The PMD compensating apparatus may also be used in a wavelength division multiplexed optical communication system.

A method of compensating an optical signal having polarization mode dispersion is also disclosed and includes: dithering a wavelength of the optical signal so as to vary around a center wavelength; compensating the polarization mode dispersion of the optical signal with a variable polarization mode dispersion compensator; polarizing an optical signal output from the variable polarization mode dispersion compensator to generate polarized component optical signals; detecting polarized component optical signals to generate detection signals; and controlling said compensating step according to the detection signals.

The polarizing step may include subjecting the optical signal output from the variable polarization mode dispersion compensator to plane polarization at a first polarization angle, plane polarization at a second angle different that the first angle, and circular polarization; the detecting step detecting the three polarized optical signals to output a first, second and third detection signal.

Control of the PMD may be further achieved by minimizing a sum of the squares of the first, second, and third detection signals.

Another polarization mode dispersion compensating system according to the invention includes: a polarization mode dispersion compensator optically coupled to an input port and receiving an input optical signal having polarization mode dispersion, said polarization mode dispersion compensator having a variable polarization mode

dispersion; a Q detector operatively coupled to said polarization mode dispersion compensator, said Q detector outputting an electrical signal representing an edge sharpness of the optical signal output from said polarization mode dispersion compensator; and a controller operatively coupled to said Q detector and to said polarization mode dispersion compensator, said controller receiving the electrical signal from said Q detector; said controller controlling said polarization mode dispersion compensator to minimize the Q represented by the electrical signal to compensate for the polarization mode dispersion of the input signal.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein:

Fig. 1 is a block diagram showing a polarization mode dispersion compensating apparatus according to the invention:

Fig. 2 is a block diagram showing an example of how a polarization controller may be implemented in the inventive polarization mode dispersion compensating apparatus;

Fig. 3 is a block diagram of a polarization mode dispersion compensating system according to a first embodiment of the invention;

Fig. 4 is a block diagram of a polarization mode dispersion compensating system according to a second embodiment of the invention;

Fig. 5 is a high-level flowchart illustrating a generalized method of polarization mode dispersion compensation;

Fig. 6 is a high-level flowchart illustrating an adaptation of the generalized method of polarization mode dispersion compensation to a particular type of PMD compensator; and

Fig. 7 is a block diagram of a wavelength division multiplexed communication system incorporation the polarization mode dispersion compensating apparatus of the invention.

DETAILED DESCRIPTION OF INVENTION

The following detailed description of the invention refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. Also, the following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims and equivalents thereof.

The expression "optically communicates" as used herein refers to any connection, coupling, link or the like by which optical signals carried by one optical system element are imparted to the "communicating" element. Such "optically communicating" devices are not necessarily directly connected to one another and may be separated by intermediate optical components or devices.

Fig. 1 illustrates the main components of the polarization compensator 100. An input port 5 receives an input optical signal 1 suffering from PMD. The input port 5 may be, for example, a connector, splice or other connection between the polarization compensator 100 and the optical fiber carrying the input signal 1.

The PMD compensator 100 of the invention seeks to counter or oppose the PMD vector of the input signal 1. To that end, two polarization mode dispersion elements (PMDEs) 20, 40 are used as sources of opposing PMD magnitude. In Fig. 1 each of the PMDEs 20, 40 has an associated PMD magnitude T. The assignation of value T is for the sake of rapid understanding as this value could vary from PMDE 20 to PMDE 40.

The PMDEs 20, 40 may be constructed with a length of fiber. To save space, these lengths of fiber are preferably constructed with fiber having a large birefringent property. By using the same fiber type and cutting each fiber section to the same length equal values of T may be obtained for the PMDEs 20, 40. As noted above, however, T may vary from PMDE 20 to PMDE 40. Moreover, PMDEs 20, 40 may be constructed with any other birefringent material or device such as a section of birefringent crystal.

Furthermore, the PMDEs 20, 40 of the invention have a relative angle θ between the polarization mode dispersions of the PMDEs 20, 40. To control this angle θ a retarder 30 is placed between and optically coupled to the PMDEs 20, 40. The retarder 30 may be constructed from a variety of devices such as a variable waveplate built from distributed bulk optic devices, liquid crystal devices, or integrated electrooptic waveguide devices as is known in the art.

The principal polarization axes of the variable retarder 30 are preferably at 45 degrees to the principal polarization axes of the PMDEs 20, 40. This relationship is indicated by the axes above each of the elements. The variability of variable retarder 30s principal axes is further indicated by an arc having two arrows.

The retarder 30 varies the angle θ between the PMD vectors T of the PMDEs 20, 40. Mathematically, the magnitude of the vector sum is $2T\sin(\theta/2)$.

The PMD compensator 100 may compensate for a differential group delay τ within a range of:

$0< \tau<2T$,

In other words, given an expected phase shift τ between the two polarization components of the input signal 1, the PMDEs 20, 40 must have a PMD sum (2T) greater than the expected phase shift τ. For greater amounts of PMD compensation, additional PMDE's or PMD compensators 100 may be combined such as in a cascade configuration.

Sub a1 To complete the PMD compensator 100 elements, a polarization ~~controller 10 is~~ optically coupled to the input port ~~5. Polarization~~ controller 10 varies the orientation the input signal's ~~polarization~~ axes to align with and oppose the polarization axes of the PMDEs ~~20, 40~~.

Polarization controller 10 may be implemented with a variety of known devices including liquid crystal devices and integrated electrooptic devices. In a bulk optic device embodiment, the polarization controller may be constructed with a pair of quarter waveplates sandwiching a half-wave plate. By rotating the quarter-waveplates, the polarization axes may be rotated.

An integrated electrooptic implementation for the polarization controller 10 could also be used in which, for example, a $LiNBO_3$ crystal is fabricated to include a waveguide structure with three cascaded electrode sections that have linear birefringence of variable

orientation but constant phase retardation. The phase retardation is a series of quarter/half/quarter phase retardation just like the bulk optic device but instead of using mechanical rotating elements a voltage may be applied to vary the orientations. Further details of such devices may be found in the literature. See, for example, USP 5,212,743.

As mentioned in the background section, the PMD of the input signal varies with time. To control the PMD compensator 100 so as to adapt to the time-varying PMD, the invention further includes a variety of structures and methods.

Fig. 3 illustrates a first embodiment of a PMD measuring and control structure. The output port 95 may include a tap, splitter or coupler that takes a portion of the output signal 99 and feeds it to a polarimeter 60.

Polarimeter 60 may be constructed in a variety of fashions as is known in the art (e.g. some of which are commercially available such as the HP-8509).

Fig. 3 provides an example of a polarimeter 60 structure according to the invention. Three polarizers 52, 54, 56 each receive a portion of the output signal 99. An internal splitter may be used to supply each of the polarizers 52, 54, 56 with a portion of the output light signal 99. As shown, the polarizers 52, 54, 56 have different polarizations (circular, plane polarization at a first angle, and plane polarization at a second angle different than the first angle ((e.g. 45 degrees to the first angle)) that respectively polarize the light incident thereon. The respectively polarized light signals then impinge photodetectors 62, 64, 66 for measurement. Each of the polarization states (P1, P2, and P3) may be represented as detected amounts (d1, d2, and d3).

Sub 02 The polarimeter 60 may include other polarizers different than or in addition to the ones shown in Fig. 4. For example, a combination of elliptical polarizers having different polarization orientations could be used as a substitute or in addition to the polarizers 52, 54, 56. For simplicity, a set of three polarizers 52, 54, 56 is sufficient for the invention to operate properly. In other words, the set of three polarizers 52, 54, 56 permits the invention to "see" polarization state with three degrees of freedom and thereby effect control over a full range of PMDs.

To further effect control, the source wavelength of the input signal 1 is dithered or otherwise varied by a small amount. Preferably, the wavelength variation in the dither is small enough to not trigger other problems such as significant cross talk with any other

channels that may be present. To dither the source wavelength, the control voltage of the source laser (e.g. a semiconductor laser device) may be varied by a small amount. The dither may be a sinusoid, square wave, triangle wave or any other wavelength variation imposed on the main signal wavelength.

Sub B a3 Dithering the source permits the PMD to be observed. Given that a signal passes through a path having PMD the output SOP changes as a function of wavelength. The invention exploits this phenomenon by intentionally varying the source wavelength and observing the resulting changes to the state of polarization SOP. When the net PMD of the communication system plus the compensator is small this results in a small change in a the dither observed by the polarimeter 60. In other words, when the PMD compensator is set correctly the observed dither in the SOP by polarimeter 60 is small.

Specifically, detectors 62, 64, 66 observe respective polarized components of this dither. The output of the detectors is an accurate measure of the input signal's PMD. The dithering wavelength shows up as a varying detection output from the detectors 62, 64, 66.

Controller 70 receives the detected, polarized components from detectors 62, 64, 66. Using a processing algorithm or digital signal processing (DSP) chip the controller 70 can recover the content of the dither (e.g. the frequency of the dither). In this way, the signal source of the optical signal need not transmit the dither content to the controller 70.

Controller 70 utilizes the detected polarized components and dither information from the detectors 62, 64, 66 to control the PMD compensator 100 so as to minimize PMD of the input signal plus the PMD of the inventive components. If the PMD compensator 100 is used, then the controller uses the detected polarized dither to control the retarder 30 and the polarization controller 10 to minimize $(d1)^2 + (d2)^2 + (d3)^2$. If another type of PMD compensator is used, then the controller 70 may adjust the control voltages of such a PMD compensator so as to minimize $(d1)^2 + (d2)^2 + (d3)^2$.

The controller 70 may be constructed with a variety of components such as computer programmed with software embodying the inventive methods. Other hardware, firmware and/or software may also be used to perform the inventive methods. Furthermore, the controller 70 may be constructed with an ASIC (application specific integrated circuit) which would add a speed advantage over a software-programmed

computer. The specific implementation and/or programming of these devices is a routine matter to one of ordinary skill in the art.

Sub a4 The controller 70 may also utilize an adaptive learning algorithm to improve the degree of control and better compensate for the PMD of the input signal 1. There are a variety of conventional adaptive learning algorithms that may be applied by the invention such as, for example, neural networks, expert systems, and statistical learning algorithms. Such adaptive learning algorithms would accept as inputs the d1, d2 and d3 values from the polarimeter 30 to generate output control signals for the polarization controller 10 and the variable retarder 30.

Preferably, the adaptive learning algorithm in the controller 70 would be permitted learn while the system is not carrying live traffic. In other words, the PMD system could be connected to a fiber receiving a test input signal 1 for a period of time sufficient for the controller 70 to adapt to the time-varying PMD of the input signal 1 and converge solutions thereto that minimize the PMD of the output signal 99. Thereafter, the input signal 1 may be a live traffic signal which could be best compensated by an already-trained controller 70. Of course, controller 70 may still continue learning while live traffic is sent through the PMD compensator 100.

Fig. 4 illustrates a second embodiment of the invention. The second embodiment shares many components with the first embodiment with the differences being in the control structure and operation. Instead of using a polarimeter 60 as in the first embodiment, the second embodiment uses a Q detector 80. The signal quality Q of the signal output from the PMD compensator 100 is a measure of the signal pulse sharpness and may be quantitatively measured using conventional techniques.

Because such Q detectors 80 typically operate on electrical signals, a O/E (optical-to-electrical) converter 45 is used. The O/E converter 45 may be constructed with, for example, a photodetector.

The controller 70 of the second embodiment shown in Fig. 4 operates in much the same way as in the first embodiment except that the input is a Q value. Based on the signal quality measure Q, the controller 70 controls the retarder 30 and the polarization controller 10 so as to maximize Q. A maximized Q corresponds to sharp pulse edge transitions which means that PMD of the input signal 1 has been minimized. In other words, PMD causes

pulse spreading and less-sharp edge transitions. Q is a measure of the edge sharpness and therefore, a measure of PMD compensation effectiveness. By maximizing Q, the controller 70 will substantially eliminate the PMD of the input signal 1.

In general, the first embodiment in which a polarimeter 60 is utilized to provide control information is generally preferred over the second embodiment in which the Q detector 80 is utilized. One reason is that the d1, d2, d3 information is more detailed and indicative of the input signal's PMD that the Q value. Thus, a more precise control and more substantial elimination of the input signal's PMD may be effectuated with the information from the polarimeter 60 than with the information from the Q detector 80.

Furthermore, current implementations of Q detectors 80 are rather slow particularly when compared with the polarimeter 60 that may be constructed with high-speed photodetectors 62, 64, 66. The reason is that the measurements and calculations necessary to detect Q are complex and time-consuming.

Fig. 5 further describes the operation of the invention and generalizes the control method to any type of polarization mode dispersion compensator having a variable polarization mode dispersion. As shown therein, the inventive method dithers the signal wavelength (200). Dithering, in and of itself, may be accomplished with a variety of devices and the inventive method may work with any such device as long as the wavelength is varied by some small amount (preferably small enough not to interfere with other components) and by a frequency high enough to effectively compensate for the time-varying PMD.

As further shown in Fig. 5, the method proceeds by compensating the optical signal's PMD (210) with a variable PMD compensator. Although the hardware described above in relation to Figs. 1-4 may be utilized, the inventive control method is not limited thereto and may include the split path approaches of, for example, Hakki; a fixed element approach (multiple or single fixed birefringent compensating elements); or any other device capable of varying PMD and to which a control signal may be applied to controllably vary the PMD.

Next, the method polarizes the output (270) of the variable PMD compensator. Any polarimeter may be used and the invention is not limited to the polarimeter 60 shown in fig. 3 and described above. The polarized components are then detected (270). Preferably, the detection step should "see" at least three distinct polarized components output from the

polarimeter in order to determine the polarization state to three degrees of freedom and thereby provide the ability to accurately control the PMD compensation (290).

If the PMD compensator 100 is used by the method, then the control step 290 may control the retarder 30 and polarization controller 10. If another PMD compensator is used, then the control step 290 would control the appropriate control voltages. To achieve PMD compensation, control step 290 preferably minimizes $(d1)^2 + (d2)^2 + (d3)^2$.

Sub a5

Fig. 6 further illustrates the adaptation of the generalized method of Fig. 5 ~~to the~~ particular PMD compensator 100 shown in Figs. 1-4. To adapt, the control step 290 would include the steps 310-340 of Fig. 6. In detail, the method would change the orientation of the polarization states (310) by controlling the polarization controller 10. The signal would then be input to the first PMDE (step 32) by supplying the signal from polarization controller 10 to the PMDE 20. The phase angle would then be retarded (330) by controlling the retarder 30. The output of the retarder is supplied to the input of the second PMDE (step 340). The method controls steps 310 and 330 to minimize $(d1)^2 + (d2)^2 + (d3)^2$. and, thereby, reduces the PMD of the input optical signal so that a compensated signal 99 is output.

Fig. 7 illustrates a WDM (wavelength division multiplexed) system 500 incorporating the invention. Because PMD varies according to wavelength, each channel of the WDM system 500 should have its own PMDC (polarization mode compensator).

Specifically, the WDM system 500 includes a plurality of transmitters Tr_1 to Tr_n (400-1 to 400-n) each of which emits one of a plurality of optical signals. Each of the plurality of optical signals are at a respective one of a plurality of wavelengths.

Furthermore each Tr_1 to Tr_n (400-1 to 400-n) imposes a dither on the respective wavelength being output therefrom. A common dither control circuit (not shown) may be used to reduce components.

The dithered optical signals are output from Tr_1 to Tr_n (400-1 to 400-n) and combined using a conventional WDM multiplexer 410, onto an optical communication path 410, comprising, for example, an optical fiber.

To transmit over long distances, chain of optical amplifiers 420-1 to 420-n are typically coupled in series along optical communication path 410. If a long distance is not being traversed or if other forms of amplification such as Raman amps are used which do

not require an amp repeater chain, then optical amplifiers 420-1 to 420-n may be eliminated entirely.

A WDM demultiplexer 440 is coupled to optical communication path 410 at the end of the amplifier chain (if present). Each of the outputs of WDM demultiplexer 410 are coupled to a respective one of PMDCs 450-1 to 450-n, which perform PMD compensation according to the techniques described above. Each of the PMDCs 450-1 to 450-n may be constructed as described above and may include the PMD compensator 100 or any other PMD compensator using the control methodologies of Fig. 5 or employing the Q detector 80 and associated control.

The PMD compensated signal 99 output from each of the PMDCs 450-1 to 450-n may then be supplied to receivers 460-1 to 460-n. Because of the PMD compensation, the BER of the received signal should be reduced with respect to an uncompensated signal.

Alternatively, a PMDC 450 may be provided at the output of an OADM (optical add drop multiplexer) to provide PMD compensation before detection of the signal or before supplying the signal to another optical path. If more than one channel is being dropped then a corresponding number of PMDCs 450 should be used to provide PMD compensation.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.